Method and system of communications

TECHNICAL FIELD OF THE INVENTION

The present invention relates to high data rate communications, and more especially it relates to line of sight,

5   LOS, multiple input multiple output, MIMO, links, such as radio links and optical wireless communications links. For reasons of simplicity elements receiving or emitting electromagnetic fields are referred to as antenna elements as, e.g., light emitters and sensors are direct correspondences

10   in light communications to antenna elements for radio wave communications.

BACKGROUND AND DESCRIPTION OF RELATED ART

High-speed wireline or fiber optic connections of backbone networks interconnecting nodes of a terrestrial radio ac-

15   cess network are previously known. It is also known to interconnect radio base stations with microwave links providing interconnections of moderate data rates.

Increased antenna area of prior art microwave link antennas increases signal quality, but also increases irradiated mi-

20   crowave power as does transmission power increases. An increased antenna area can be achieved by arranging a plurality of smaller area antenna elements in an array.

Efficient modulations and signal constellations offer relieved power requirement, or improved performance if micro-

25   wave power is maintained, as number of signal points in the signal constellation increases.

American Patent Application US2003/0125040 discloses a system for multiple-input multiple-output (MIMO) communication. A MIMO channel formed by N_T transmit antennas and N_R

30   receive antennas is decomposed into N_C independent channels

also referred to as spatial sub-channels, where $N_C \leq \min\{N_T, N_R\}$. Data is processed prior to transmission based on channel state information.

American Patent Application US2002/0039884 reveals a radio communication system with a transmitter having a plurality of transmitter antennas and a receiver having at least one antenna. Thereby a plurality of paths with various characteristics are formed between the transmitter antennas and the at least one receiver antenna. Data is assigned one or more categories. Depending on categories and path characteristics, the data is mapped to one or more of the transmitter's parts and antennas.

American Patent Application US2002/0039884 describes a radio communication system with a transmitter having a plurality of transmitter antennas and a receiver having at least one antenna. Data tags indicate data importance or other requirements. Data is assigned one or more categories. Depending on categories and path characteristics, the data is mapped to one or more of the transmitter's parts and antennas.

3rd Generation Partnership Project (3GPP): Technical Specification Group Radio Access Network, Physical layer aspects of UTRA High Speed Downlink Packet Access (Release 4), 3G TS 25.848 v4.0.0, France, March 2001, describes MIMO open loop signal processing of MIMO transmitter and receiver in section 6.5.

Bell Labs Technical Journal, autumn 1996: G. Foschini, "Layered Space- Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas" shows that under fading conditions with statistically uncorrelated identically distributed propagation

channels, the bandwidth constrained channel capacity of a MIMO channel, C_{MIMO}, scales on average as

$$C_{SISO} \cdot \min\{M,N\}, \tag{1}$$

where C_{SISO} is channel capacity of a SISO channel, and M and N are number of antenna elements at receiver and transmitter side, respectively. For a band limited (bandwidth B) AWGN (Additive White Gaussian Noise) channel the SISO channel capacity equals

$$C_{SISO}=B \cdot \log_2(1+SNR_{SISO}) \text{ [bits/s],} \tag{2}$$

where SNR_{SISO} is the SISO channel signal to noise ratio.

Figure 1 schematically illustrates N transmitter antenna elements «T_1, T_2,…, T_N» and M receiver antenna elements «R_1, R_2,…, R_M» in MIMO communications. Between the various transmitter and receiver antenna elements there are propagation channels «h_{11}, h_{12},… h_{1M},…, h_{NM}».

The individual propagation channels, that are SISO (Single Input Single Output) channels, form a MIMO channel.

C. Schlegel and Z. Bagley, *"Efficient Processing for High-Capacity MIMO Channels"* submitted to JSAC, MIMO Systems Special Issue: April 23, 2002 reveals estimation of optimum channel capacity of a MIMO system for a known MIMO-channel described by channel matrix **H** by means of singular value decomposition, SVD.

$$\mathbf{U} \cdot \mathbf{S} \cdot \mathbf{V}^H = SVD\{\mathbf{H}\}, \tag{3}$$

where **U** and **V** are unitary matrices, **S** is a resulting diagonal matrix with singular values in the main diagonal, and $\mathbf{V}^H$ is a Hermitian transformed matrix **V**.

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A. Goldsmith, S. A. Jafar, N. Jindal, S. Vishwanath, "Capacity Limits of MIMO Channels" IEEE Journal on Sel. Areas in Comm., Vol. 21, No. 5, June 2003 provides results on ca-pacity gain obtained from multiple antennas in relation to
5   channel information at receiver or transmitter, channel signal-to-noise ratio, and correlation between channel gains of each antenna element. The paper also summarizes results for MIMO broadcast channel, BC, and multiple access channel, MAC, and discusses capacity results for multicell
10   MIMO channels with base station cooperation, the base sta-tions acting as a spatially diverse antenna array.

In accordance with Goldsmith et al., the MIMO channel ca-pacity for flat fading channel conditions, in the case of equal number of antenna elements for transmitter and re-
15   ceiver antennas, is

$$C_{\text{MIMO}} = B \cdot \log_2 \left(\det\{\mathbf{I} + \frac{\text{SNR}}{N} \mathbf{H} \cdot \mathbf{H}^H\} \right) \quad \text{[bits/s]}, \qquad (4)$$

assuming uncorrelated channels of the various sending an-tenna elements.

P. Kyritsi, "MIMO capacity in free space and above perfect ground: Theory and experimental results" 13th IEEE Interna-tional
20   Symposium on Personal, Indoor and Mobile Radio Com-munications 2002, vol.1, pp. 182- 186, Sept. 2002 studies the capacity potential for propagation in free space over perfect ground. Theoretical predictions are compared with measurements over an empty parking lot with nearly flat
25   surface.

None of the cited documents above discloses particular an-tenna configurations related to communications distance with line of sight, LOS, MIMO communications.

SUMMARY OF THE INVENTION

Next generation radio access networks are expected to be
required to support peak user data rates in the order of
magnitude of 30 Mbps - 1 Gbps. With a vast amount of base
5   stations, it would be advantageous to interconnect base
stations over radio links for flexibly connecting/discon-
necting links of a mobile station active set of radio links
with the base station as the mobile station moves.

Present radio link solutions do not offer sufficient data
10   rates of aggregate user data, as to/from a base station,
including a plurality of high rate user data links at rea-
sonable power levels for reasonably sized element antenna
apertures.

Consequently, there is a need of antennas of large aper-
15   tures providing required data rates at reasonable transmis-
sion power for reasonably sized element antenna apertures.

It is consequently an object of the present invention to
achieve an antenna configuration for line of sight communi-
cation useful for providing low error rates at moderate
20   transmission power within limits as may be required by due
authorities.

It is also an object to achieve a system flexible to dif-
ferent transmission ranges and wavelength ranges.

An object is also to offer high data rates for low trans-
25   mission power levels as regards antenna properties.

Another object is to achieve an antenna configuration
adapted to particular communications distance and wave-
length.

Finally, it is an object to relieve the dependency on tan-
gible interconnections, such as wire lines or optical fi-
bers, for interconnection of base stations or other nodes
of a telecommunications system. Such interconnections are
5   generally associated with great initial investment costs
and maintenance costs.

These objects are met by a method and system of antennas
configured for a particular communications distance over
line of sight links providing multiple input multiple out-
10   put communications links.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 schematically illustrates N transmitter antenna
elements and M receiver antenna elements in MIMO communica-
tions.

15   Figure 2 schematically illustrates a spherical wave-front
background to the invention.

Figure 3 illustrates example capacity versus SNR_{SISO} for
four-element LOS MIMO linear array, according to the inven-
tion, and four-element linear array non-LOS MIMO.

20   Figure 4 illustrates a square grid LOS MIMO antenna array,
according to the invention.

Figure 5 illustrates an example rectangular array with
four rows and three columns of elements according to the
invention.

25   Figure 6 shows a linear LOS MIMO antenna array, according
to the invention.

Figure 7 illustrates an equilateral triangular antenna
realization according to an embodiment of the invention.

Figure 8 depicts a spatially oversampled antenna array, according to the invention.

Figure 9 demonstrates hexagonal antenna element packing, according to the invention.

5   Figure 10 has an antenna array with circular element packing, according to the invention.

Figure 11 displays a clustered directional hybrid with eight groups of clustered antenna elements for eight channels MIMO, according to the invention.

10   Figure 12 shows a clustered directional hybrid with four groups of clustered antenna elements for four channels MIMO, according to the invention.

Figure 13 illustrates a clustered directional hybrid with two groups of clustered antenna elements for two channels
15   MIMO, according to the invention.

Figure 14 comprises plotted capacity per bandwidth vs. normalized SNR for MIMO communications with square grid LOS MIMO antennas for various levels of clustering at both receiver and transmitter side, according to the invention.

20   Figure 15 shows an LOS MIMO antenna array with director elements, according to the invention.

Figure 16 depicts schematically an LOS MIMO antenna with a grid of interconnected rods or tensed wires to which the antenna elements are attached, according to the invention.

25   Figure 17 illustrates a two-layer square grid LOS MIMO antenna with two layers of antenna elements each on a square grid.

Figure 18 illustrates a realization according to the invention with equal distances between all nearest neighboring antenna elements, the antenna elements being positioned to the vertices of a cube.

5   Figure 19 illustrates a realization according to the invention with equal distances between all nearest neighboring antenna elements, the antenna elements being positioned to the vertices of a tetrahedron.

DESCRIPTION OF PREFERRED EMBODIMENTS

10 In backbone networks based on wireless communications it is important to achieve capacity to handle data rates of aggregate traffic, where individual peak user data rates are in the order of 100 Mbps to 1 Gbps.

Fixed fiber optical networks are not always applicable.
15 They are often associated with great costs, provide little or no flexibility and occupy extensive ground space.

Prior art Multiple Input Multiple Output, MIMO, communications systems most commonly are designed to utilize scattering and, therefore, requires a scattering environment.

20 The present invention is not dependent on such scatterers and suits line of sight communication very well. A theoretical reason for this is its exploitation of spherical wave fronts and associated phase differences.

Figure 2 schematically illustrates propagation paths and
25 principles of the invention. Respective propagation paths «p_{11}», «p_{12}», «p_{13}» between a transmitter antenna «T1» and receiver antennas «R_1», «R_2», «R_3» differ slightly in length due to a spherical wave front property of the transmitted signal. The small differences in path lengths «δ_{11}», «δ_{12}»,
30 «δ_{13}» add to the communications distance D. With path p_{ij} as

a reference for the communications distance, δ_j equals zero. I.e. when p_{11} is selected as reference then $\delta_{11}=0$. The antenna configuration according to the invention essentially maximizes MIMO channel capacity for great signal to noise

5   ratios, SNR, in respect of the spherical wave front property for LOS communications. This is in contrast to, e.g., maximizing antenna directivity as illustrated in and explained in relation to figure 14 below.

With each MIMO sub-channel operating close to its maximum

10   theoretical performance, according to the configuration of the invention, great performance gains are achieved.

Figure 3 illustrates example capacity versus SNR_{SISO} for LOS MIMO and non-LOS MIMO (fading uncorrelated channels) for a four-element linear array. For the comparison illustrated

15   in figure 3, non-LOS MIMO array antenna elements are assumed to be placed such that the antenna elements experience channels with no or negligible cross correlation. In a typical local scattering environment, this is achieved by placing the antenna elements separated by half a wave-

20   length. The illustrated capacity of LOS MIMO is achieved for a system according to the invention. The gain of LOS MIMO as compared to non-LOS MIMO in terms of capacity increase or SNR gain is the vertical or horizontal difference between the curves, respectively. The SNR gain implies,

25   e.g., increased noise immunity or reduced transmission power requirement.

Radio Access Networks, RANs, are frequently realized with base stations connected in series, with at least one of the serialized base stations serving as an anchor to the core

30   network. Consequently, the individual links between base stations may carry data traffic of a plurality of base stations. With individual peak user data-rates in the range

of 100 Mbps - 1 Gbps required peak rates of data links be-
tween base stations could be expected to be in the range of
1-100 Gbps.

Prior art radio data links is not known to provide data
5   rates of more than one Gbps for the spectrum efficiency
achieved with the invention. The major two reasons for
this are that there are practical limits on signal constel-
lation sizes, practical and regulatory constraints on
available radio spectrum, and power limits.

10 Prior art relies upon uncorrelated channels between the
various antenna elements. This could e.g. be the case for
channels fading due to scattering. The presumption, how-
ever, normally does not hold for LOS communications over
wireless links, such as e.g. radio links. However, the in-
15 vention points out that exploitation of the spherical prop-
erty of wave fronts results in ideal MIMO gain in absence
of scatterers. According to the invention rectangular or
square grid LOS MIMO antenna array and linear LOS MIMO an-
tenna arrays are preferred, see figures 4 and 6 respec-
20 tively. This does not exclude circular or hexagonal pack-
ing as a means to increase antenna elements surface density
as illustrated in figures 9 and 10 respectively. In the
hexagonal packing of figure 9 the respective distances be-
tween (at most 6) nearest neighboring antenna elements «An-
25 tenna element» are all essentially equal «d». Spatially
oversampled and clustered antenna arrays, see figure 8 and
11 respectively, are preferred for some situations. Fig-
ures 12 and 13 show some other clustered directional hy-
brids for 16 antenna elements «Antenna element».

30 With reference to figures 11-13, while the total number of
antenna elements, N, are kept constant equal to 16 elements
the respective number of groups of elements, k $(1 \leq k \leq N)$, of

the figures varies. In figure 11 there are eight groups with two antenna elements «Antenna element» each. Within each group the antenna elements «Antenna element» are positioned sufficiently close for signals to add coherently in phase, thereby generating a directivity gain. Figure 13 illustrates an example realization with four groups, each of four antenna elements «Antenna element». In figure 13, an example for $N=16$ and $k=2$ is illustrated. In the figures each group of antenna elements «Antenna element» generates a MIMO sub-channel. With N/k antenna elements for each MIMO sub-channel on receiver and transmitter side, the total achievable gain is $(N/k)^2$, since both sides contribute to the gain. If equivalent isotropic radiated power, EIRP, is at its maximum level allowed, the gain at transmitter side is achieved as a reduction of transmit power and not in increased received power or energy per symbol. Assuming an SNR gain of $(N/k)^2$ for grouped directional antennas with k groups, equations (1) and (2) transform into

$$C_{\text{clustered}}=B\cdot k\cdot \log_2 \left(1+\frac{N^2}{k^2}\text{SNR}_{\text{SISO}}\right) \quad [\text{bits/s}]. \qquad (5)$$

There are SNR ranges where MIMO communications with clustered elements antennas outperform MIMO with the same number of antenna elements, not being clustered. As noted in figure 14 a channel capacity increase is achieved with clustering particularly for poor transmission conditions (small SNR). Figure 14, plots the channel capacity per bandwidth $C_{\text{clustered}}/B$ for MIMO communications with clustered antenna elements versus SNR «SNR$_{\text{SISO}}$» normalized to SISO communications conditions, and where k is the number of clusters of antenna elements at transmitter and receiver ends, $k \in [1,N]$. The figure illustrates performance for an example of 16 antenna elements according to equation (5), with SISO

performance of $N=1$ antenna element antennas included for reference.

Typically high SNR conditions prevail in short range communications. Consequently, gain increase by unclustered MIMO communications with great number of antenna elements is preferred for short-range communications.

For high SNR, the MIMO channel capacity in (4) is approximate to

$$C_{MIMO} = f\left(\left|\mathrm{Det}\{\mathbf{H}\}\right|^2\right) \quad [\mathrm{bits/s}], \tag{6}$$

where f is a monotonically increasing function of one variable and $|\cdot|$ denotes absolute value. (Equations (4) and (6) turn out to be maximized by the same maximizing channel matrix, $\mathbf{H} = \mathbf{H}^{opt}$.) The inventors observe that the channel matrix $\mathbf{H}$ can be separated into a Kronecker product of two matrices, $\mathbf{H}_v$ and $\mathbf{H}_h$.

$$\mathbf{H} = \mathbf{H}_v \otimes \mathbf{H}_h , \tag{7}$$

where $\mathbf{H}_v$ is of dimension $N_v \times N_v$ and $\mathbf{H}_v$ is of dimension $N_h \times N_h$, N_v being the number of vertical antenna elements and N_h being the number of horizontal antenna elements. The determinant in equation (6) then rewrites

$$\left|\mathrm{Det}\{\mathbf{H}\}\right| = \left|\mathrm{Det}\{\mathbf{H}_v\}\right|^{N_h} \cdot \left|\mathrm{Det}\{\mathbf{H}_h\}\right|^{N_v} . \tag{8}$$

A further observation according to the invention is that each of $\mathbf{H}_v$ and $\mathbf{H}_h$ can be separated

$$\mathbf{H}_v = \mathbf{H}_{v1} \cdot \mathbf{H}_{v12} \cdot \mathbf{H}_{v2} , \tag{9}$$

$$\mathbf{H}_h = \mathbf{H}_{h1} \cdot \mathbf{H}_{h12} \cdot \mathbf{H}_{h2} , \tag{10}$$

where the determinants

$$\det\{\mathbf{H}_{v1}\}=\det\{\mathbf{H}_{v2}\}=1 \quad , \tag{11}$$

$$\det\{\mathbf{H}_{h1}\}=\det\{\mathbf{H}_{h2}\}=1 \quad , \tag{12}$$

and that the matrices $\mathbf{H}_{v12}$ and $\mathbf{H}_{h12}$ are Vandermonde matrices. In a final step of observing it is noted that

$$\det\{\mathbf{H}_{v12}\}\leq (N_v)^{N_v/2} \quad , \tag{13}$$

$$\det\{\mathbf{H}_{h12}\}\leq (N_h)^{N_h/2} \quad . \tag{14}$$

In equations (13) and (14), the maximum is attained for vertical and horizontal distances d_v and d_h, respectively,

$$d_v=\sqrt{\frac{D\lambda}{N_v}} \quad , \text{ and} \tag{15}$$

$$d_h=\sqrt{\frac{D\lambda}{N_h}} \quad . \tag{16}$$

5   For a generalized rectangular grid array with N_h elements in each row and N_v elements in each column, communicating at a frequency corresponding to wavelength λ over a communications distance D, the optimum antenna elements distances in equation (15) and (16) converts to antenna dimensions equal

10   to

$$h=(N_v-1)\sqrt{\frac{D\lambda}{N_v}} \quad , \text{ and} \tag{17}$$

$$w=(N_h-1)\sqrt{\frac{D\lambda}{N_h}} \quad . \tag{18}$$

Figure 5 illustrates an example rectangular array with four rows and three columns of elements, each row comprising antenna elements separated a distance d_h, and each column comprising antenna elements separated distance d_v. According

15   to the invention the preferred antenna element distances

are determined in accordance with equations (15) and (16).
The dimension (Width×Height) of the antenna array is then
$w^{opt} \times h^{opt}$.

In figure 6, for an optimum MIMO system and for a communi-
cations distance D much greater than element separation d
the distance $a=d(N-1)$ is specified by

$$a = (N-1)\sqrt{\frac{D\lambda}{N}} \qquad\qquad (19)$$

$$\approx \sqrt{D\lambda N}, \qquad\qquad (20)$$

where the approximation in equation (20) holds for great
number of antenna elements N. For $N=16$ antenna elements
«Antenna element», the approximation error is about 7%.
Table 1 illustrates element separation, d, of a transmitter-
receiver pair of linear MIMO antennas versus communications
distance, D, at some example wavelengths, λ, equal to 3 mm,
7.9 mm and 42.9 mm.

Distance D [km]	Element separation d [m]		
	$\lambda=3$ mm	$\lambda=7.9$ mm	$\lambda=42.9$ mm
0.2	0.55	0.9	2.1
2	1.7	2.8	6.5
20	5.5	8.9	20.7
200	17.3	28.1	65.4

Table 1: Linear MIMO antenna, $N=2$.

For the square grid LOS MIMO antenna array in figure 4, the
distance a, corresponding to that of equation (19) for lin-
ear arrays, is determined to $a=(\sqrt{N}-1)d$

$$a = \left(\sqrt{N} - 1\right) \frac{\sqrt{D\lambda}}{\sqrt[4]{N}} \tag{21}$$

$$\approx \sqrt{D\lambda} \cdot \sqrt[4]{N}, \tag{22}$$

where the approximation in equation (22) holds for great number of antenna elements N. For $N=16$ antenna elements «Antenna element», the approximation error is about 33%. An important observation is that for the square grid LOS
5   MIMO antenna array in figure 4 the distances a and d get relatively smaller in proportion to the fourth root of N, whereas for the linear array of figure 6 the distance dependency is proportional to the square root of N.

With the antenna area $A=a^2$, and using the approximation in
10   equation (22), the MIMO channel capacity, $C_{MIMO}=N \cdot C_{SISO}$, expressed in terms of channel capacity for a SISO system, C_{SISO}, with the example design of figure 4 according to the invention is

$$C_{MIMO} \approx \left(\frac{A}{D\lambda}\right)^2 C_{SISO} \tag{23}$$

In figure 4 and equation (21) the antenna elements «Antenna
15   element» are assumed to be electrically active elements, supplying a voltage or current to a receiver. However, as illustrated below basically the same distance relations hold for antenna elements being directors guiding received electromagnetic field to electrically active antenna ele-
20   ments.

Figure 7 illustrates an equilateral triangular antenna realization according to an embodiment of the invention. The antenna elements are all separated by d_{tri}. Similarly to

the rectangular realization in figure 5, the optimum an-
tenna element separation of the equilateral triangular an-
tenna structure with three antenna elements equals $\sqrt{D\lambda/3}$,

where D is communication distance and λ is communication

5   wavelength.

Figure 15 illustrates a realization with director elements
«Director» mounted on supports «Supports». The directors
«Director» direct electromagnetic fields received and elec-
tromagnetic fields to be transmitted, preferably with one

10   director per electrically active antenna element «Active
elements». Preferably the directors «Director» are pure
reflectors but can also be made of dielectric material.
The supports «Supports» are designed not to shadow, or only
have a small shadowing impact on, the electrically active

15   antenna elements «Active elements». The positioning of the
directors is preferably in accordance with equation (19)
and (21) for a linear and square grid LOS MIMO antenna re-
spectively. The relevant distance d is essentially equal to
the separation distance of the projection of the directors

20   onto a plane, the plane being perpendicular to the LOS
transmission path to the other receiver/transmitter end.
Advantages achieved by the realization of figure 15 in
addition to those mentioned above are, e.g., simplified
wiring of the antenna elements and the antenna elements

25   spanning a smaller distance range thereby being mechani-
cally robust. Also, by adjusting the directors the elec-
trically active antenna elements need not always be reposi-
tioned even if communications distance changes.

The dependency of a, A and $d_v/d_h/d$ on D for an LOS MIMO an-

30   tenna has practical implications, addressed by the inven-
tion. An obvious solution to the problem of getting a, to
the communications distance D, appropriately matched ele-

ment distance, d_v, d_h, d, is to manufacture custom-made an-
tennas. From a cost perspective, however, a more attrac-
tive solution is manufacturing of a set of antenna models
for MIMO communications, each designed for a range of com-
5   munications distances D, and upon installation selecting an
antenna model within the set that best matches the communi-
cations distance. For frequency non-selective channels,
SVD (singular value decomposition) provides robustness and
close to optimum performance also with non-perfect matching
10 of communications distance, D, and element separation, d_v,
d_h, d. Another embodiment is realized by individually ad-
justable antenna elements. Preferably this is realized by
a grid «Grid» of interconnected rods or tensed wires to
which the antenna elements «Antenna element» are attached
15 as illustrated in figure 16. The wires or rods are pref-
erably connected to a frame «Frame». Models that are elec-
tromechanically adjustable comprise electromechanical mo-
tors to which the rods are connected, such that the rods to
which the antenna elements «Antenna element» are attached
20 may move along the frame. A further embodiment of adapting
an LOS MIMO antenna to communications distance D uses spa-
tial oversampled antennas as schematically illustrated in
figure 8 and activating the antenna elements by signal
processing providing best performance at actual communica-
25 tions distance. The particular element distribution may be
varied, e.g. as illustrated in figures 9 and 10. An impor-
tant issue of the invention is that active elements are
distributed such that their mutual distances reflects com-
munications distance (distance between transmit and receive
30 antennas) and wavelength such that the spherical properties
of the radio wave can be exploited.

It is observed that as transmitter and receiver antennas
form an antenna pair for a communications link, the respec-

tive element distances d_v, d_h and d in e.g. equations (15) and (16) of an example transmitter antenna can be reduced (or increased) if the element distance of a corresponding example receiver antenna of the communications link is in-

5   creased (or reduced) in proportion to the distance reductions (or increase) of the transmitter antenna. Indexing distances of transmitter and receiver antennas by T and R, respectively, if respective element distances of a receiver antenna, d_{vR}, d_{hR} and d_R, are reduced (or increased) in rela-

10 tion to an initially determined distance d_v, d_h or d, transmitter-side antenna-element distance, d_{vT}, d_{hT} and d_T, should be increased (or reduced) in proportion thereto (in relation to d_v, d_h and d). Consequently, the distances d_v, d_h in equations (15) and (16) are the geometrical averages of

15 receiver and transmitter antenna element distances, respectively.

The actual antenna dimensions in equations (17) and (18), of course, are determined by actual respective vertical and horizontal element distances. Correspondingly, also an-

20 tenna dimensioning in equations (19) and (21) are determined by actual distances, if adjusted as described above. At transmitter side equations (17), (18), (19) and (21) translate to equations (24), (25), (26) and (27)

$$h_T = (N_{vT}-1)\, d_{vT} \;, \tag{24}$$

$$w_T = (N_{hT}-1)\, d_{hT} \;, \tag{25}$$

$$a_T = (N_T-1)\, d_T \;, \quad \text{and} \tag{26}$$

$$a_T = \left(\sqrt{N_T}-1\right) d_T \;, \tag{27}$$

and correspondingly for receiver side, they translate to
25 equations (28), (29), (30) and (31)

$$h_R = (N_{vR}-1)\, d_{vR} \quad, \tag{28}$$

$$w_R = (N_{hR}-1)\, d_{hR} \quad, \tag{29}$$

$$a_R = (N_R-1)\, d_R \quad, \quad \text{and} \tag{30}$$

$$a_R = \left(\sqrt{N_R}-1\right) d_R \quad, \tag{31}$$

where

$$d_v = \sqrt{d_{vR} \cdot d_{vT}} \quad, \tag{32}$$

$$d_h = \sqrt{d_{hR} \cdot d_{hT}} \quad, \tag{33}$$

$$d = \sqrt{d_R \cdot d_T} \quad. \tag{34}$$

The invention does not only cover planar antenna configura-
tions, but also three-dimensional configurations as illus-
trated in figures 17-19. Figure 17 illustrates a two-layer
5   square grid LOS MIMO antenna with two layers of antenna
elements each on a square grid. Figures 18 and 19 illus-
trate realizations with equal distance between all nearest
neighboring antenna elements. In figure 18 the antenna
elements are positioned to the vertices of a cube and in
10 figure 19 the antenna elements are positioned to the verti-
ces of a tetrahedron.

Various embodiments of the invention also cover different
realizations of signal processing at transmitter and re-
ceiver ends. The processing is necessary for adaptation to
15 prevalent channel conditions. At receiver or transmit
side, determining channel singular values as described in
relation to equation (3) and singular value decomposition
can be achieved by digital signal processing of base band
signals. If determined at transmitter side, information on
20 channel matrix, **H**, need to be transferred from receiver

side, or the channel matrix otherwise estimated at trans-
mitter side, see figure. For a 2×2 channel matrix, singu-
lar value decomposition can also be achieved by a 3-dB hy-
brid to perform multiplication or weighting as need be, op-
5   erating on high-frequency signals. Also, for channel ma-
trices greater than 2×2 a generalization of a 3-dB hybrid,
a Butler matrix directional coupler, may be used. A fur-
ther embodiment realizes the processing by means of an ar-
rangement of microstrip or waveguides, also operating on
10   high-frequency signals. At receiver side, channel equali-
zation requires processing. This processing can be per-
formed by any of the processing realizations described for
transmitter side, or received signal can be equalized by
means of zero forcing, for which the received signal being
15   multiplied by the inverse matrix of channel matrix H, or by
means of minimum mean square error, MMSE, for which the
mean square error is minimized, the various processing re-
alizations giving rise to further embodiments.

If there is multipath propagation, this is preferably in-
20   corporated into the singular value decomposition at trans-
mitter side through feedback information. Corresponding
information can also be derived through channel reciprocity
if the reverse direction channel matrix is determined at
transmitter side (the transmitter side also comprising ra-
25   dio receiver). Another solution comprises a self-tuning
antenna, optimizing performance at receiver side, transmit-
ter side or both. The antenna element positioning is then
adapted to channel propagation properties corresponding to
a measured channel matrix, H. This can be achieved by,
30   e.g. a stochastic gradient algorithm. Particularly for
fixed positioned antenna elements, they may require the an-
tenna elements to be re-distributed for optimum perform-
ance. For an electromechanically adjustable element an-

tenna the optimization can be achieved by automatic posi-
tion adjustments of the antenna elements.   The different
solutions to multipath propagation can also be combined.

Preferably and in accordance with the invention, singular
5   value decomposition is applied, to flat (frequency non-
selective) fading channels.   If a channel nevertheless is
frequency-selective fading, the channel can be considered
piecewise flat fading for sufficiently small frequency in-
tervals.   Such piecewise flat fading channels can, e.g., be
10   achieved by dividing a given frequency range or bandwidth
using orthogonal-frequencies sub-carriers of sufficiently
narrow one or more bandwidths for the one or more band-
widths to be much less than the coherence bandwidth.   One
technique for achieving such sub-carriers is orthogonal
15   frequency division multiplex, OFDM.

The concept of the present invention combines well with
other known means to increase throughput, such as transmis-
sion at both vertical and horizontal polarization or trans-
mission at left-hand and right-hand circular polarization,
20   or different coding of different sub-channels depending on
their respective channel quality, which further demon-
strates the usefulness of the invention.   Such combinations
are also within the scope of this invention.

Dimensioning has been expressed in relation to particular
25   orientation, e.g. horizontal or vertical orientation, re-
ferring to orthogonal directions, perpendicular to the di-
rection of communications.   However, this does not exclude
rotation of receiver and transmitter antennas in a plane
parallel to the antenna elements, with corresponding rota-
30   tion of both antennas such that their mutual orientation is
preserved.   Despite somewhat inappropriate, the notation of
vertical and horizontal is kept for reasons of simplicity.

The invention is not intended to be limited only to the embodiments described in detail above. Changes and modifications may be made without departing from the invention. It covers all modifications within the scope of the following
5   claims.